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1. Your reference ~~SP 2036~~ Jg-3156-PCT

2. Patent application number *(The Patent Office will fill in this part)* 0406765.8 26 MAR 2004

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*
Southampton Photonics Limited
3 Wellington Park
Tollbar Way
Southampton
SO30 2QU

Patents ADP number *(if you know it)* 7894330003

If the applicant is a corporate body, give the country/state of its incorporation UK

4. Title of the invention
Apparatus for Providing Optical Radiation

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

GRAHAM JONES & COMPANY,
77 BEACONSFIELD ROAD,
BLACKHEATH,
LONDON,
SE3 7LG.

PFS 1/77
28/7/04

Patents ADP number *(if you know it)* 2097001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Number of earlier application	Date of filing *(day / month / year)*

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a) any applicant named in part 3 is not an inventor, or
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Claim(s)	
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11. I/We request the grant of a patent on the basis of this application.

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Apparatus for Providing Optical Radiation

Field of Invention

This invention relates to an apparatus for providing optical radiation. The invention has particular relevance for welding, drilling and cutting applications using lasers in factory environments in which scatter from ceilings and other surfaces represents a safety hazard, and for low heat generation in high-power fibre lasers.

Background to the Invention

Fibre lasers are increasingly being used for materials processing applications such as welding, cutting and marking. Their advantages include high efficiency, robustness and high beam quality. Examples include femtosecond lasers for multiphoton processing such as the imaging of biological tissues, Q-switched lasers for machining applications, and high-power continuous-wave lasers.

Traditional lasers used for material processing applications predominate at around 1.06μm and longer wavelengths such as provided by a carbon dioxide laser (10.6μm). These lasers are being supplemented by fibre lasers operating at around 1.06μm. Light scattered from the work piece when using such fibre lasers is a problem because the scatter is at wavelengths at which the retina of the eye can be easily damaged.

It is of interest to have eye safe wavelengths for scatter light considerations. This means wavelengths longer than 1400nm, and preferably between 1500nm and 2500nm. Erbium is a suitable dopant for fibre lasers outputting in the 1550nm wavelength window. Erbium doped fibres can be pumped at a variety of wavelengths, including by high-power diode lasers operating between 915nm and

980nm. Unfortunately, the erbium doped fibre is not very efficient when pumped at 915nm and this leads to undesirable heat generation within the erbium doped fibre.

It is also of interest to improve the thermal management of fibre lasers so as to reduce the problem of heat generation within a high power fibre laser. The main source of heat generation is due to the quantum defect (ie the difference in photon energy between the pump and the laser photons). This means that the pump and laser wavelengths should be as close together as possible.

It is also preferable to use silica fibre because of its heat resistance, low loss properties, and the fact that it can be spliced.

Laser diodes have reduced life if they are pulsed and this therefore limits the life of high power fibre lasers pumped that are pumped by laser diodes. A solution is to accept diode failures and to provide redundancy. Commercial systems available to day can use between 10% to 20% more laser diodes than would otherwise be required if the laser diodes were more reliable. It would be of interest to improve the reliability of pulsed fibre lasers that are pumped by laser diodes.

An aim of the present invention is to provide an apparatus for providing optical radiation that reduces at least one of the above aforementioned problems.

Summary of the Invention

According to a non-limiting embodiment of the present invention, there is provided apparatus for providing optical radiation comprising a plurality of laser diodes, at least one first amplifying waveguide, and at least one second amplifying waveguide, in which the second amplifying waveguide is pumped by the first amplifying waveguide, and the first amplifying waveguide is pumped by the laser

diodes, the apparatus being characterised in that the first amplifying waveguide is configured to improve the beam quality of radiation emitted by the laser diodes.

The apparatus may include at least one multimode beam combiner for combining optical radiation emitted by the laser diodes.

The apparatus may include at least one first beam combiner for combining optical radiation emitted by the first waveguides.

The first amplifying waveguide may comprise a first optical fibre. The first optical fibre may comprise a core and a cladding. The first optical fibre may be singlemode or multimode. The first optical fibre may comprise a plurality of cores. The first optical fibre may comprise a region comprising a first rare-earth dopant.

The second amplifying waveguide may comprise a second optical fibre. The second optical fibre may comprise a core and a cladding. The second optical fibre may be singlemode or multimode. The second optical fibre may comprise a plurality of cores. The second optical fibre may comprise a region comprising a first rare-earth dopant.

The apparatus may include means to change the wavelength of radiation emitted by the first amplifying waveguide. The means may be a wavelength tuneable reflector, an optical switch, a source of optical radiation, or a tuneable grating. The tuneable grating may be thermally tuned, or tuned by an actuator.

The apparatus may be configured such that the optical radiation emitted by the second amplifying waveguide has a higher brightness when the first amplifying optical fibre emits at a first wavelength. This is a particularly advantageous implementation of the invention, useful for modulating high-power fibre lasers that are pumped by a plurality of laser diodes. Instead of switching the laser diodes on and off, the fibre laser can be controlled with a lower power signal. Advantages

include increasing the life of the laser diodes, and removing the need for switching electrical power. Additionally, as will be described in this specification, the invention allows distributed thermal management and shorter, more powerful lasers – particularly at so-called "eye-safe" wavelengths.

The apparatus may be in the form of an amplifier, a laser, a master oscillator power amplifier, a Q-switched laser, a source of amplified spontaneous emission, or a continuous wave laser.

Brief Description of the Drawings

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 shows an apparatus for providing optical radiation according to the present invention;

Figure 2 and 3 show cladding pumped optical fibres;

Figure 4 shows an apparatus comprising a plurality of first fibre pump modules;

Figure 5 shows an apparatus which is end pumped;

Figure 6 shows an apparatus containing a plurality of second fibre pump modules;

Figure 7 shows an apparatus in the form of a master oscillator power amplifier;

Figure 8 shows an apparatus in the form of a continuous wave laser;

Figure 9 shows an apparatus including an actuator; and

Figure 10 shows an apparatus including a source of optical radiation 111.

Detailed Description of Preferred Embodiments of the Invention

With reference to Figure 1, there is provided apparatus 10 for providing optical radiation 15 which apparatus comprises a plurality of laser diodes 3, at least one first amplifying waveguide 1, and at least one second amplifying waveguide 2, in which the second amplifying waveguide 2 is pumped by the first amplifying waveguide 1, and the first amplifying waveguide 1 is pumped by the laser diodes 3, the apparatus being characterised in that the first amplifying waveguide 1 is configured to improve the beam quality of radiation emitted by the laser diodes 3.

The first amplifying waveguide 1 is preferably a cladding pumped optical fibre such as the first amplifying fibre 20 shown in Figure 2. The first amplifying fibre 20 comprises a first core 21 and a first cladding 22, and first rare earth dopant 23 in at least one of the first core 21 and the first cladding 22. Also shown is a coating 24 which may be a glass or a polymer. The refractive index of the coating is preferably less than the refractive index of the first cladding 22.

The second amplifying waveguide 3 is preferably a cladding pumped optical fibre such as the second amplifying fibre 30 shown in Figure 3. The second amplifying fibre 30 comprises a second core 31 and a second cladding 32, and second rare earth dopant 33 in at least one of the second core 31 and the second cladding 32.

The first and second cladding 22, 32 may be solid or may comprise longitudinally extending holes. Longitudinally extending holes are advantageous for guiding pump radiation without the pump radiation "seeing" the coating 24. This therefore has thermal dissipation advantages in that metal coatings can be used which would otherwise attenuate the pump radiation as it propagates along the cladding. The metal coatings may be soldered to a heat sink.

The first and second amplifying fibres 20, 30 are shown with a second cladding 24 which may comprise a glass or a polymer. The second cladding 24 may be solid or may contain longitudinally extending holes.

Referring to Figure 1, the second amplifying fibre 2 may be part of a GTWave fibre 8 which contains the second amplifying fibre 2 and at least one pump fibre 7 surrounded by a common coating 9. The second amplifying fibre 2 and the pump fibre 7 are in optical contact along at least a portion of their length.

The invention is particularly useful for application in high power fibre lasers emitting optical radiation 15 between 1500nm and 2500nm. For example, if the second rare earth dopant 33 is erbium and the pump diodes 3 emit optical radiation at 976nm, then the conventional solution for pumping the second amplifying optical fibre 30 would be to combine the optical radiation from the laser diodes 3 and couple the radiation into the second amplifying optical fibre 30. This approach leads to large diameters of the second cladding 31 (for example 500um to 5mm) and inefficient absorption of the pump radiation by the second amplifying optical fibre 30 which leads to undesirable heat generation. The inclusion of the intermediary stage involving the first amplifying fibre 1 permits brightness conversion, that is the multimoded pump radiation emitted by the diode lasers 3 is converted to pump radiation having a higher beam quality in order to pump the second amplifying fibre 20. Thus for example, the first rare-earth dopant 23 may be erbium codoped with ytterbium, and pump radiation at a wavelength of 910nm to 920nm and/or 970 to 980nm can be used to cladding pump the first amplifying fibre 20 whose first core 21 may be single mode (or multimode or contain a plurality of single mode or multimode cores) and be configured to emit radiation at 1530nm (or 1520nm to 1550nm), a convenient wavelength for in-band pumping the second rare earth dopant 33. It is then possible to reduce the cross-

sectional dimensions of the second cladding 32 than would otherwise be possible, resulting in increased absorption and thus shorter fibre length. Advantageously, the invention also provides a method of distributing the thermal dissipation in several stages. This is particularly advantageous for providing high power (100W to 10kW) optical radiation 15 in the eye safe 1500 to 1650 wavelength window as the efficiency of cladding pumped erbium doped amplifiers can be relatively low (eg 25% to 30%) if pumped from 915nm. The advantages combine to give an apparatus that is very advantageous for materials processing applications where the control of thermal dissipation near the work piece and the eye safe wavelengths provide excellent safety advantages over existing systems.

Referring to Figure 1, the apparatus may include first reflectors 4 and second reflectors 5 in order to form a laser cavity in the first amplifying waveguide 1. The first and second reflectors 4, 5 may be mirrors, reflectors, gratings, or fibre Bragg gratings. If the first rare-earth dopant 23 is Erbium codoped with ytterbium, then it is advantageous to separate out the photosensitive region (typically doped with germinia) which is used to form the fibre Bragg grating from the region doped with the first rare-earth dopant 23 (which would require phosphorus co-doping). The first amplifying waveguide 1 may comprise a single core 21 which may be single moded or multimoded. Alternatively, the first amplifying waveguide 1 may comprise a plurality of cores 21 which may be single moded or multimoded. A fibre amplifying optical fibre comprising multiple single mode cores is advantageous because it facilitates the writing of single mode fibre Bragg gratings in each of the cores. The cores can be spaced sufficiently far apart so as not to cause interference effects.

Also shown in Figure 1 are first beam combiners 11 which combine the pump radiation from the laser diodes 3. The first beam combiners 11 can be multimode

beam combiners that can incorporate tapers in order to couple from an input fibre 12 to the first amplifying fibre 1. Beam combiners are available which can couple the power from three, seven, nineteen or higher numbers of fibres. Alternatively, the first beam combiners 11 can comprise lenses, splices between fibres of different diameters, or etched fibre sections.

The pumps 3, first beam combiner 11, first amplifying fibre 1, and first and second reflectors 4, 5 comprise a first fibre pump module 17 as shown in Figure 1.

Figure 4 shows an apparatus 40 comprising second fibre pump modules 43 which comprise a plurality of the first fibre pump modules 17 whose outputs are combined in a second beam combiner 41. The second fibre pump modules 43 are used to pump the second amplifying fibre 2. The second beam combiners 41 may combine the outputs of between 2 and 64 first fibre pump modules 17, with 3, 7, and 19 being preferred numbers.

The pump diodes 3 may be single emitters which are currently available at power levels of 5W to 10W. If the first and second beam combiners 11, 41 each combine 19 inputs, then continuous wave output power levels up to 3.6kW multiplied by the efficiency of the first amplifying fibre 1 are achievable. Assuming 25% efficiency (for erbium pumped pumped at 915nm and emitting at 1532nm), the second amplifying fibre 2 shown in Figure 4 can be pumped by up to 4kW of pump energy with the majority of the wasted energy being dissipated in the first fibre pump modules 17. The invention thus provides a method of achieving eye-safe laser radiation at high powers with the benefit of distributing the thermal heat load to avoid concentrating inefficiencies in the final stage.

Figure 5 shows an apparatus in which a fibre pump source 50 pumps a second amplifying fibre 30 in an end-pumped configuration. The fibre pump source 50 is either the first or second fibre pump source 17, 43.

Figure 6 shows an apparatus comprising a plurality of the fibre pump sources 50 coupled into the second amplifying fibre 30 by side couplers 62. The side couplers can take many forms known in the art for cladding pumping fibre amplifiers and lasers including the fibre arrangement 9 shown in Figures 1 and 4.

Figure 7 shows an apparatus in the form of a master oscillator power amplifier (MOPA) 70 comprising a seed source 71 and a first and second amplifiers 72, 73. Also shown is an optional optical isolator 73 for preventing undesirable feedback into the first amplifier 72. The first amplifier can be a conventional optical amplifier, the apparatus 10 shown in Figure 1, or the apparatus 40 shown in Figure 4. The second amplifier 73 can be the apparatus 10 shown in Figure 1 or the apparatus 40 of Figure 4. The seed source 71 can be a laser diode, a fibre laser, a Q-switched laser, a gas laser, or a solid-state laser. The seed source 72 is selected such that the second amplifying fibres 2 in the first and second amplifiers 72, 73 provide amplification when pumped by the pump diodes 3.

Figure 8 shows an apparatus in the form of a continuous wave laser 80 comprising the first and second amplifiers 72, 73, and first and second reflectors 81, 82.

Although the description pertaining to eye safety and the selection of the second rare earth dopant 33 concentrate on erbium, the second rare earth dopant 33 may be selected from the group comprising erbium, holmium and thulium. The rare earth dopant 33 may be co-doped with ytterbium. This has been found to be advantageous for erbium ytterbium doping when utilizing in-band pumping even

though the ytterbium has no spectroscopic function. The ytterbium appears to increase the efficiency of the erbium, possibly by improving its solubility. Ytterbium codoping also appears to avoid other deleterious effects such as clustering which can give rise to up conversion.

The invention is also useful for other wavelength regimes. Thus the first and second rare earth dopants 23, 33 can be selected from the group erbium, ytterbium, holmium, terbium, and neodymium.

The laser diodes 3 can be broad stripe laser diodes. Alternatively or in addition, at least some of the laser diodes 3 can be diode bars or diode stacks. The first beam combiner 11 can be a lens or a fused taper coupler such as described in United States patent US 5864644, which is hereby incorporated herein by reference. The pump fibre 7 may be a high numerical aperture multimode optical fibre.

The apparatus 10 is in the form of a source of amplified spontaneous emission or an amplifier. The apparatus 10 can be configured as a laser which may be pulsed or continuous wave.

Figure 10 shows an apparatus in which the wavelength of radiation emitted by the first amplifying waveguide 1 can be changed by an actuator 101 attached to the second reflector 5 in first fibre pump module 102. The actuator 101 and second reflector 101 combination is a tuneable wavelength reflector which can be a grating that is thermally tuned or tuned by application of stress and/or strain. Thus for example, the first amplifying fibre 1 can be doped with ErYb and emit optical radiation normally at around 1μm. If the first and second reflectors 4, 5 are selected to reflect in the wavelength range 1500nm to 1550nm, then by tuning the reflectivity of at least one of them (by wavelength and/or amplitude) the first amplifying fibre 1 can be turned into a laser emitting at 1500nm to 1550nm. If the second amplifying

fibre 2 is doped with Er then the Erbium can be pumped in a manner that is controllable by the actuator 101. The second amplifying fibre 102 can contain reflectors 105, 106 which may be mirrors, gratings or fibre gratings configured such that apparatus 100 lases when pumped in the wavelength range 1500nm to 1550nm. This can be achieved if the reflectors 105, 106 reflect at longer wavelengths, say at 1560nm.

An alternative means for changing the wavelength of radiation emitted by the first amplifying waveguide 1 is shown in Figure 11 in which a source of radiation 111 is included in each first fibre pump module 112. The source of radiation 111 can be a laser that is controlled by application of a signal. Advantageously, the first amplifying waveguide 1 may contain ErYb dopant and the first fibre pump module 112 may be configured by first and second reflectors 4, 5 to emit radiation at 1090nm. Preferably the first and second reflectors 4, 5 would have relatively low reflectivity (0.1% to 10%) in order to clamp the gain. This can be advantageous to prevent spontaneous pulses from damaging the apparatus. Injection of radiation in the wavelength range 1500nm to 1550nm by the source of radiation 111 (which may be a laser diode or fibre laser) of sufficient power level will cause the first amplifying fibre 1 to amplify the radiation and thus pump the second amplifying fibre 2 (preferably doped with Erbium) in order to emit the desired optical radiation 15. Thus control of the source of radiation 111 can be used to modulate the optical radiation 15 which is beneficial for many high power laser applications because it avoids modulating the laser diodes 3.

Other means for changing the wavelength of radiation emitted by the first amplifying waveguide 1 include a wavelength tuneable reflector and an optical switch.

In general the first amplifying fibre 1 in Figures 10 and 11 can be designed such that it can emit optical radiation at a first wavelength λ1 or a second wavelength λ2 in response to a signal (not shown). And the second amplifying fibre 2 is then designed such that the optical radiation 15 has a higher brightness when the first amplifying optical fibre 1 emits at the first wavelength λ1 than the second wavelength λ2. This is a particularly advantageous implementation of the invention, useful for modulating high-power fibre lasers that are pumped by a plurality of laser diodes. Instead of switching the laser diodes on and off, the fibre laser can be controlled with a lower power signal. Advantages include increasing the life of the laser diodes, and removing the need for switching electrical power. Additionally, as described in this specification, the invention allows distributed thermal management and shorter, more powerful lasers – particularly at so-called "eye-safe" wavelengths.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance performance.

The present invention extends to the above-mentioned features taken in isolation or in any combination.

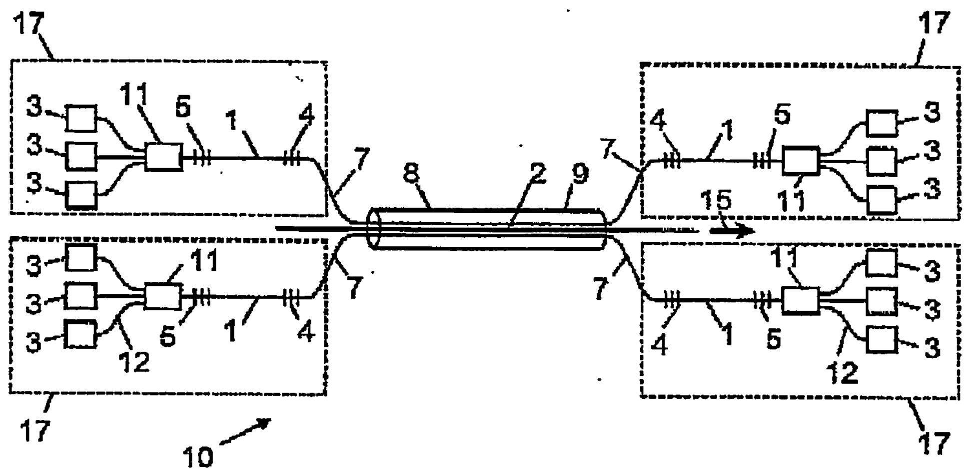

FIG 1

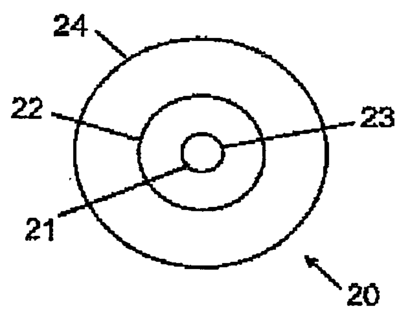

FIG 2

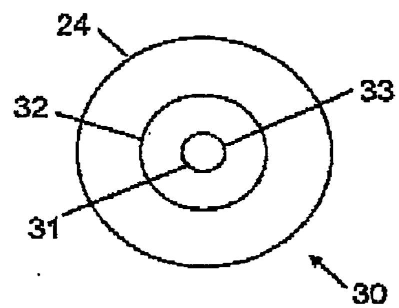

FIG 3

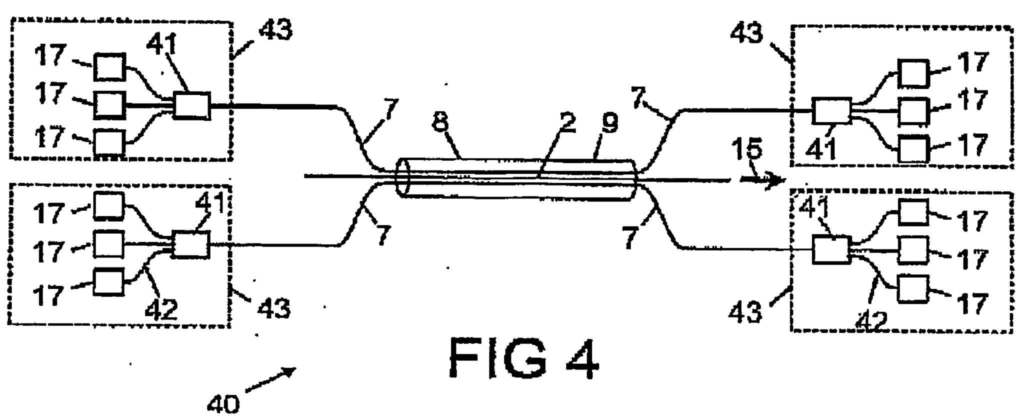

FIG 4

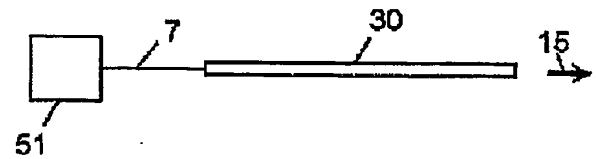

FIG 5

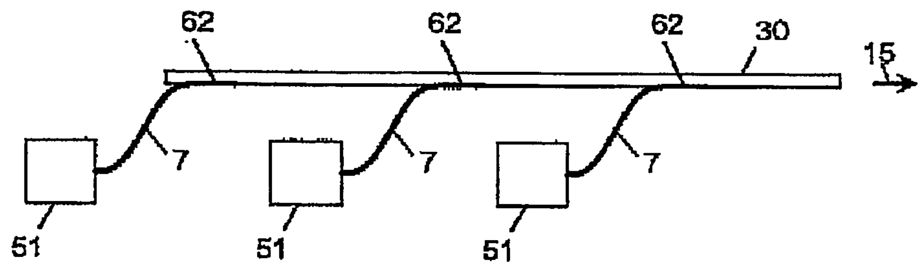

FIG 6

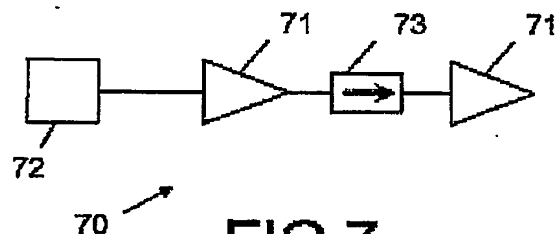

FIG 7

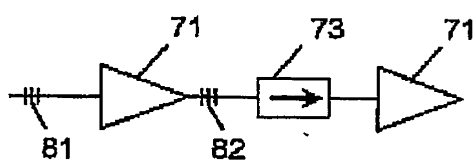

FIG 8

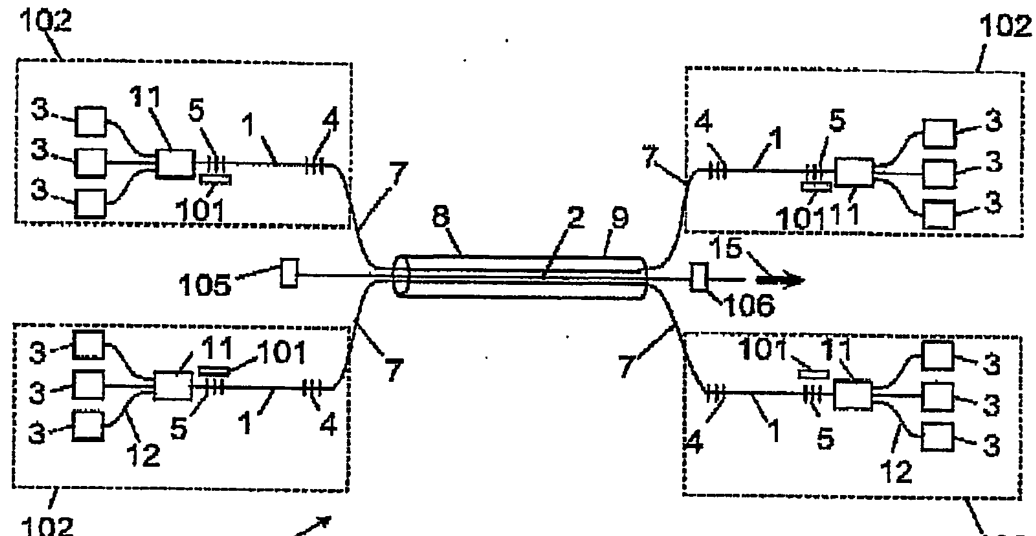
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FIG 10

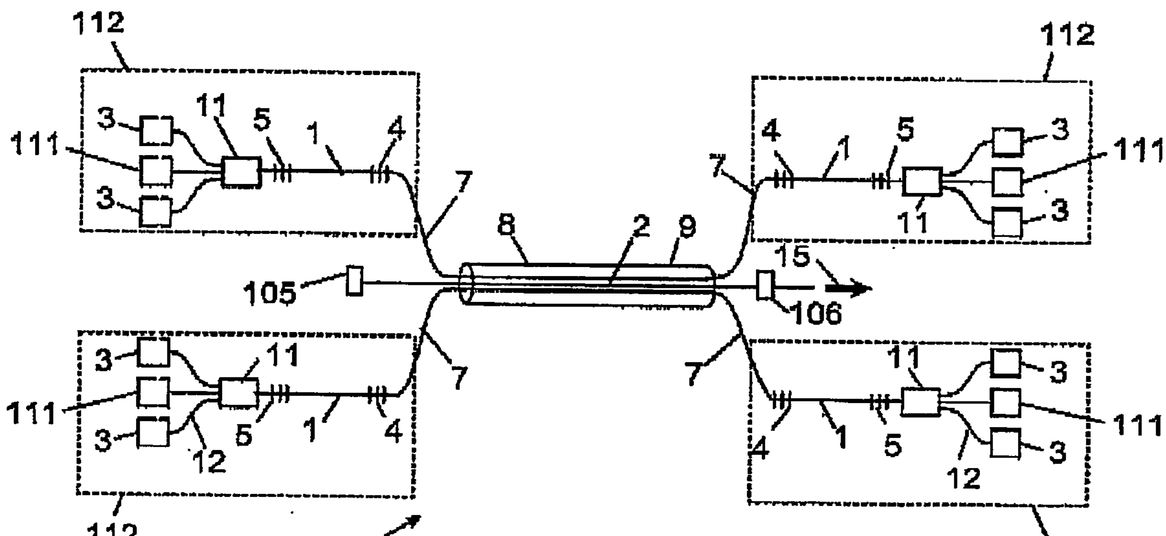
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FIG 11